Drone Detection

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***Abstract*—Unmanned Aerial Vehicle technology studies increased to an extent, that has made it possible to become a big asset in military organizations. Due to its characteristics such as remote control, low cost, small size and other advantages, it already has a wide range of applications making it prerequisite to detect UAVs for protection. This paper presents different experiments using different systems for the detection of small aerial targets like UAVs, especially small drones.**

***Index Terms*—drone, UAV, detection, radar, frequency, band.**

I. Introduction

Arial space is a resource that can be used in many different ways and ever since people have invented the first aircraft, they came up with ways that bring profit such as: means of transport for people or even objects (using planes), military activities (using fighter jets, bombers, unmanned aerial vehicles - UAVs etc.), mass media, corporate and recreational use (using UAVs).

Due to the low-cost, there is a fast evolution regarding UAVs that have great capabilities, thus some threats have appeared. The first challenge is to detect these UAVs: because some UAVs are small, they can be detected very hard or they might not even be detected. Once detected, the next step is to determine whether counter measures are necessary or not.

Radar surveillance remains the primary source of information in the predictable future. Other means such as optical, acoustic and laser sensors will appear depending on technology development.

Most of the UAVs after being detected are vulnerable to a variety of different air defense systems: anti-aircraft artillery, shoulder-fired man portable systems and radar directed low medium and high altitude surface to air missile systems. [1]

UAVs have tactical advantages in military activities such as: being able to carry payloads, being able to record in real time during reconnaissance (this method saves more lives), being able to thermal scan using heat vision cameras or even being used for target practice for different missile systems.

In the next pages of this article different UAV classifications will be presented.

The Department of Defense of the United States of America had a Defense Science Board Study on Unmanned Aerial Vehicles and Uninhabited Combat Aerial Vehicles [1].

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Due to the cost of some equipment, the UAVs have not been typically equipped with sophisticated electronic countermeasures suits and/or radar warning systems.

For some of the smaller UAVs, their small size and quiet engines is an advantage because it reduces the probability of detection but for other UAVs that are bigger, it does not reduce the probability of detection. Incorporated stealth technology might help in that domain.

UAVs can be used in regions where the air defense threats have already been eliminated almost completely, due to vulnerability of air defense.

There are also situations, even if the air defense threats still exist, where using UAVs have more advantages, such as: providing extended surveillance in denied areas prior to conflict and/or operating early in a conflict in a tactical reconnaissance role.

II. UAV and UAS Clasiffication

The strategic concept of employment for unmanned aerial vehicles is consistent with three classes: class I - less than 150 kg, class II - from 150 kg to 600 kg and class III - more than 600 kg [2].

In class I there are three categories: Micro, mini and small. In the micro category, UAVs weigh less than 2 kg, their normal operating altitude (above ground level) is up to 200 feet, their range is 5 km in the line of sight. An example is the black widow. In the mini category, UAVs weigh between 2 and 20 kg, their normal operating altitude (above ground level) is up to 3000 feet, their range is 25 km in the line of sight. Some examples are: Scan Eagle, Skylark, Raven, DH3, Aladin and Strix. In the small category, UAVs weigh more than 5 kg, their normal operating altitude (above ground level) is up to 5000 feet, their range is 50 km in the line of sight. Some examples are: Luna and Hermes 90.

In class II there are tactical UAVs, that can reach up to 10.000 feet for the normal operating altitude (above ground level) and their range is up to 200 km in the line of sight. Some examples are: Sperwer, Iview 250, Hermes 450, Aerostar and Ranger.

In class III UAVs fall into three categories: fighter, high altitude long endurance (HALE) and medium altitude long endurance (MALE). In the fighter category, the normal operating altitude is up to 65.000 feet, the range is unlimited, beyond line of sight. In the HALE category, the normal operating altitude is up to 65.000 feet, the range is unlimited, beyond line of sight. An example of a HALE UAV is the Global Hawk. In the MALE category, the normal operating altitude (mean sea level) is up to 45.000 feet, the range is unlimited, beyond line of sight. Some examples are: Predator A, Predator B, Heron, Heron TP, Hermes 900.

The Association for Unmanned Vehicle Systems International (UVSI) has classified the Unmanned Aircraft System (UAS) in nine categories. [3]

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In the first category there are the nano UAVs (such as Hornet 1 made in Norway, Delfly made in the Netherlands) micro UAVs (such as LADF made in the USA, Mite made in USA, Carolo C4 made in Germany, Wasp I made in the USA and DragonSlayer made in the USA), mini UAVs (such as SensorCopter made in Germany, Copter I made in France, Tracker made in France and SkyLark I made in Israel) and the mini (aerostat) UAVs (such as Airstar made in France, Skive made in Switzerland and GT AirCat made in France).

In the second category there are Close Range (CR) UAVs (such as RMax II made in Japan, Luna made in Germany, Camcopter made in Austria, CybAero made in Sweden, SkyLark II made in Israel, Sky Blade II made in Singapore, Silver Fox made in USA) and Short Range (SR) UAVs (such as Vulture MK II made in South Africa, S-100 made in Austria, Sojka III made in Czech Republic and Fulmar made in Spain).

In the third category there are Short Range (SR) UAVs (such as Golden Eye 50 made in the USA, Phoenix made in UK, Pchela made in Russia, Crecerelle made in France) and Medium Range (MR) UAVs (such as KZO made in Germany, Eagle Eye made in the USA).

In the fourth category there are Medium Range Endurance (MRE) UAVs (such as Watchkeeper made in Israel, Sperwer made in France, E-Hunter made in Israel, Seeker II made in South Africa, Falco made in Italy and Shadow 600 made in the USA) and Low Altitude Deep Penetration (such as Carapas made in Italy, and Nibbio made in Italy).

In the fifth category there are Low Altitude Low Endurance (LALE) UAVs (such as Scan Eagle made in the USA, Aerosonde MK III made in Australia, Libelulle made in France) and MALE UAVs (such as Predator A made in the USA, Eagle 1 made in France, Hermes 1500 made in Israel, A-160 Hummingbird made in USA, Bateleur made in South Africa and Heron TP made in Israel).

In the sixth category there are MALE UAVs (such as Altair made in the USA, Global Observer made in USA, Predator B made in the USA and Snark made in New Zeland).

In the seventh category there are HALE UAVs (such as EuroHawk made in the USA and Global HAWK made in USA) and Stratospheric Long Endurance (STRALE) UAVs (such as: Odysseus made in the USA and EuroHawk).

In the eighth category there are Unmanned Combat Air Vehicle (UCAV) such as Corax made in UK, Sharc made in Sweden, Sky-X made in Italy, X-45A made in the USA etc.

In the ninth category there are mixt piloted UAVs (Optionally piloted aircrafts – OPA and Converted Manned Aircrafts) such as Busard made in Germany, LittleBird made in the USA, Eagle made in Malaysia, Irkut 850 made in Germany, Patroller made in Germany Herti 1A made in UK, Herti 1D made in Poland etc. [3].

III. Radar Waves and Frequency Ranges

The spectrum of the electric magnetic waves shows frequencies up to 10^{24} Hz. This range is subdivided because of different physical qualities in different sub ranges. [4]

The European Union (EU), NATO, and the United States Military have agreed on a set of EU-NATO-US ECM frequency bands for electromagnetic frequencies used mainly for radars. It does not have good coverage of the lower frequencies used in radio and specialized radar systems.

The EU-NATO-US frequency classification is presented in Table I [5].

Table I. EU-NATO-US Frequency Classification

Frequency range	Wavelength	EU-NATO-US band
Up to 250 MHz	Up to 1.2 m	A band
250-500 MHz	1.2m – 600 cm	B band
500 MHz – 1 GHz	600 cm – 300 cm	C band
1 – 2 GHz	300 cm – 150 cm	D band
2 – 3 GHz	150 cm – 100 cm	E band
3 – 4 GHz	100 cm – 75 cm	F band
4 – 6 GHz	75 cm – 5 cm	G band
6 – 8 GHz	5 cm – 3.75 cm	H band
8 – 10 GHz	3.75 cm – 3 cm	I band
10 – 20 GHz	3 cm – 1.5 cm	J band
20 – 40 GHz	1.5 cm – 750 mm	K band
40 – 60 GHz	750 mm – 500 mm	L band
60 – 80 GHz	500 mm – 300 mm	M band

The Institute for Electrical and Electronic Engineers (IEEE) has defined a system of IEEE frequency bands for electromagnetic frequencies used for radio and radar. The terminology is used extensively for radar, especially in civilian systems.

The EU-NATO-US frequency bands are especially used in electronic warfare.

The IEEE starts at 1 GHz, the designations below for the lower frequencies come from the International Telecommunication Union frequency bands.

The IEEE frequency classification is presented in Table II [6]:

Table II. IEEE Frequency Classification

Frequency range	Wavelength	IEEE band
300 kHz – 3 MHz	1 km – 100 m	MF (Medium Frequency)
3 – 30 MHz	100 m – 10 m	HF (High Frequency)
30 – 300 MHz	10 m – 1 m	VHF (Very High Frequency)
300 MHz – 1 GHz	1 m – 10 cm	UHF (Ultra High Frequency)
1 – 2 GHz	30 cm – 15 cm	L band
2 – 4 GHz	15 cm – 5 cm	S band
4 -8 GHz	5 cm – 3.75 cm	C band
8 – 12 GHz	3.75 cm – 2.5 cm	X band
12 – 18 GHz	2.5 cm – 1.6 cm	Ku band
18 – 26 GHz	1.6 cm – 1.2 cm	K band
26 – 40 GHz	1.2 cm – 750 mm	Ka band
40 – 75 GHz	750 mm – 40 mm	V band
75 – 111 GHz	40 mm – 28 mm	W band
Above 111 GHz	Millimeter wave	

The International Telecommunication Union (ITU) has defined a system of terminology for electromagnetic frequencies used for radio and radar. Its categories are too coarsely grained for describing radar uses, however, it is a good set of terms used in communications.

The ITU frequency classification is presented in Table III [7]:

Table III. ITU Frequency Classification

Frequency range	ITU band
3 – 30 Hz	ELF (Extremely Low Frequency)
30 – 300 Hz	SLF (Super Low Frequency)
300 Hz – 3 kHz	ULF (Ultra Low Frequency)
3 – 30 kHz	VLF (Very Low Frequency)
30 – 300 kHz	LF (Low Frequency, long wave)
300 kHz – 3 MHz	MF (Medium Frequency, medium wave)
3 – 30 MHz	HF (High Frequency short wave)
30 – 300 MHz	VHF (Very High Frequency)
300 MHz – 3 GHz	UHF (Ultra High Frequency)
3 – 30 GHz	SHF (Super High Frequency)
30 – 300 GHz	EHF (Extremely High Frequency)

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"Radar systems work in a wide band of transmitted frequencies. The higher the frequency of a radar system is, the more it is affected by weather conditions such as rain or clouds. The higher the transmitted frequency is, the better the accuracy of the radar system is".

The waves and frequency ranges used by radars are illustrated in Fig. 1 [4].

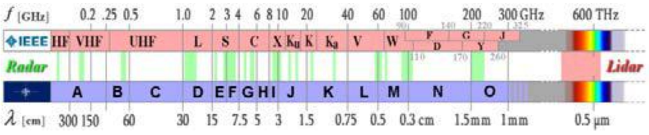

Figure 1. Waves and frequency ranges used by radars [4].

In the A and B Band (HF and VHF – Radar), the radar bands below 300 MHz have a long historical tradition because these frequencies represented the frontier of radar technology during World War II. Today these frequencies are used for early warning radars called Over The Horizon (OTH) Radars. Using these lower frequencies it is easier to obtain high – power transmitters. The attenuation of the electro-magnetic waves is lower than using higher frequencies. On the other hand, accuracy is limited, because a lower frequency requires antennas with very large physical size which determines angle accuracy and angle resolution.

In the C Band (UHF – Radar) there are some specialized Radar sets developed for this frequency band. This band is mostly used for the operations of radars which detect and track satellites and ballistic missiles over a long range. These radars operate for early warning and target acquisition like the surveillance radar for the Medium Extended Air Defense System (MEADS).

The new technology of Ultra wide band (UWB) radars uses all frequencies from A to C Bans. UWB radars transmit very low pulses in all frequencies simultaneously. They are technically used for material examination and as Ground Penetrating Radar (GPR) for archaeological explorations.

The D Band (L – Radar) is preferred for the operation of long-range air-surveillance radars out to approximately 400 km. They often transmit pulses with high power, broad bandwidth and an intrapulse modulation. Due to the curvature of the earth the achievable maximum range is limited for targets flying at low altitude. These objects disappear very fast behind the radar horizon.

In Air Traffic Management, long-range surveillance radars like the Air Route Surveillance Radar works in this frequency band. Coupled with a Mono pulse Secondary Surveillance Radar, they use a relatively large, but slower rotating antenna.

The designator D-Band is good as mnemonic rhyme for large antenna or long range.

In the E-F Bands (S – Radar) the atmospheric attenuation is higher than in the D-Band. Radar sets need a considerably higher transmitting power than in lower frequency ranges to achieve a good maximum range.

Special Airport Surveillance Radars (ASR) are used at airports to detect and display the position of aircraft in the terminal area with a medium range up to 100 km. An ASR detects aircraft position and weather conditions in the vicinity of civilian and military airfields.

The designator S-Band is good as mnemonic rhyme for smaller antenna or shorter range.

In the G-Band (C – Radar) there are many mobile military battlefield surveillance, missile – control and ground surveillance radar sets with short or medium range. The size of the antennas provides an excellent accuracy and resolution. The influence of bad weather conditions is very high, therefore air-surveillance radars use an antenna feed with circular polarization often.

This frequency band is predetermined for most types of weather radar used to locate precipitation in temperate zone like Europe.

In the I-J Bands (X and Ku Radars) the relationship between used wave length and size of the antenna is considerably better than in the lower frequency bands. The I, J Bands are relatively popular radar bands for military applications like airborne radars for performing the roles of interceptor, fighter, and attack of enemy fighters and of ground targets. A very small antenna size provides a good performance. Missile guidance systems at I, J bands are of a convenient size, therefore they are of interest for applications where mobility and light weight are important and very long range is not major requirement.

This frequency band is widely used for maritime civil and military navigations radars. Very small and cheap antennas with a high rotation speed are adequate for a fair maximum range and good accuracy. Slotted waveguide and small patch antennas are used as radar antenna, under a protective radom mostly.

This frequency band is also popular for spaceborne or airborne imaging radars based on Synthetic Aperture Radar (SAR) both for military electronic intelligence and civil geographic mapping.

In the K Band (K and Ka Radars) the higher the frequency is, the higher the atmospheric absorption and attenuation of the waves are, otherwise the achievable accuracy and the range resolution rise too. Radar applications in this frequency band provide short range, very high resolution and high data renewing rate. Using very short transmitting pulses of a few nanoseconds affords a range resolution, that outline the aircraft so it can be seen on the radars display.

In the V Band, because of the molecular dispersion (the influence of the air humidity), this frequency band stay for a high attenuation. Radar applications are limited for a short range of a couple of meters here.

In the W band, there are two visible phenomena: a maximum of attenuation at about 75 GHz and a relative minimum at about 96 GHz. Both frequency ranges are in use practically.

There are radar sets operating at 96 to 98 GHz as laboratory equipment so far. These applications give a preview for a use of radar in extremely higher frequencies as 100 GHz [4].

In the next pages of this article different experiments regarding detecting types of UAVs using different types of radars that operate in different band frequencies will be presented.

IV. UAV DETECTION

Target tracking and its parameters are the result of Air surveillance. They are transmitted continuously to the command control system and is realized in four phases: detection, recognition, identification and localization [8].

Detection is a process of identifying with undeniable probability the existence of an object in the airspace. In practice, this indicates a target shift to the target monitoring system (also known as "scanning").

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Recognition represents the match between the detected object and the category of Means of Air Attack (MoAA). After the recognition is made subsequent procedures are chosen.

Identification is the out-turn, which defines type, affiliations that are not ambiguous, priority level and additional characteristics. Even if the object is wrongly identified as "target" it is still being processed and tracked by the airspace control authorities.

The out-turns of localization are the coordinates and their derivate of the target. It is also known as "tracking". After the four phases, the target is passed to the engagement.

The phases described above, last several seconds during which the recognition and identification phases are often blending thanks to the use of the Identification Friend or Foe system (IFF). Within the Air force system architecture command control, all phases described above and their operation run almost parallel and in real time because command control entities are designed as interconnected components for reconnaissance and fire control. The whole system is called Command, Control, Communications, Computers Intelligence, Surveillance and Reconnaissance (C4ISR).

If radars are being used for target detection in aerial space, it is important to take into consideration two aspects: the target and the radar itself.

When the radar is used for Low Slow and Small (LSS) target detection, the most important factor is the Radar Cross Section (RCS) of the target. The limits of the radar lie in its carrier frequency *f*, or wavelength λ. The additional influences (internal and external) are inquiries of particular radar technical solution, tactical employment within the terrain and combat formation, atmospheric condition, proficiency of crews etc.

For a particular target to be detected, a proper wavelength which corresponds to the appropriate RCS, must be selected. The radar usability of certain wavelengths in view of the expected target range detection is illustrated in Fig. 2.

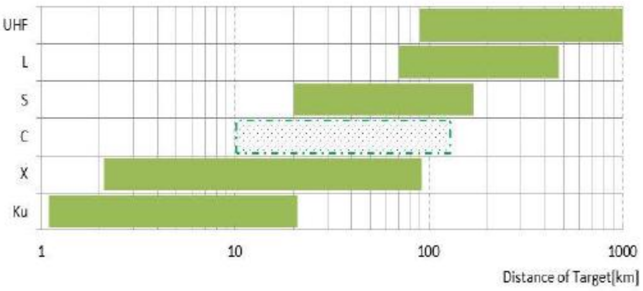

Figure 2. Radar Band versus Target Distance

Using the figure above it is not viable to say in which band it is possible, or impossible to detect a certain object. Explicit influence of atmosphere to the high frequency energy propagation is taken into account. The standard requested parameters of the output signal (accuracy) needed for further processing and following engagement by active air defense means is considered [8].

Some practical trials were done in competence of the domestic producer and air defense troops authorities of the Czech Army General Staff using Quadcopter Tarot FY650 and Hexacopter DJI S8000 as targets and the ReVISOR radar (very short air – defense) for a radius up to 10 km. The radar works in the X band, pulse mode. The experiment is detailed in [8].

The radar managed to detect the quadcopter (empty) and the hexacopter (empty and carrying a load). The quadcopter has the smallest RCS and the hexacopter carrying a load has the biggest RCS. The two UAVs that were used in the experiment are presented in Fig. 3.

Figure 3. Left Quadcopter Tarot FY650, right Hexacopter DJI S8000

The basic steps used for the experiment are: RCS computation using simulation, RCS measurement in non-reflected chambers and tests of UAV detection, exploring the radar.

Another experiment was done using a pulse Ku band radar and three different sized UAVs. The study is oriented on theoretical analysis of the detection probability versus Signal Noise Ratio (SNR) for the UAVs with low RCS. The experiment is detailed in [9].

The used UAVs (Iris+, X8, High One) are presented in Fig. 4.

Figure 4. Upper left - Iris+, upper right - X8, lower center - High One

The UAVs can be detected by the Ku-band short range pulse battlefield radar.

The basic steps used for the experiment are: RCS measurements inside an anechoic chamber in the frequency range 3 – 24.5 GHz, SNR estimation from UAV radar signal and radar range and probabilistic characteristics estimations.

Another experiment was done using a W – band radar and a UAV (a quadcopter named DJI Phantom presented in Fig. 5). The experiment is detailed in [10].

The advantages of the millimeter wave regime are the ability to be sensitive for small object structures and the insignificant effects of multipath scattering.

Figure 5. DJI Phantom

Another experiment was done using a Ka – band radar and two UAVs (a quadcopter - DJI Phantom 2 and octocopter DJI S1000 premium presented in Fig. 6) at the Air Force Institute of Technology in Poland. The experiment is detailed in [11].

Figure 6. Left - DJI Phantom 2, right - octocopter DJI S1000

In the experiment two modes of operation for drone detection — area mode and barrier mode were taken into consideration.

The area mode with a wide beam is to be used for detection, tracking and imaging UAVs in specific areas. An example of this mode is presented in Fig. 7.

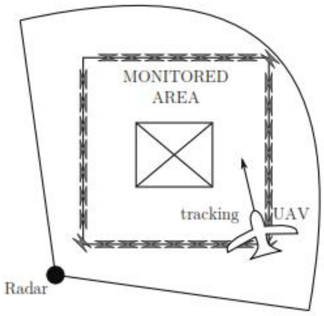

Figure 7. Principle of area mode

The barrier mode, using a narrow beam radar, is more suitable in the situation where moving objects that can cause false alarms or highly reflective objects that can saturate the radar receiver are in the restricted area. This mode is shown in Fig. 8 [11].

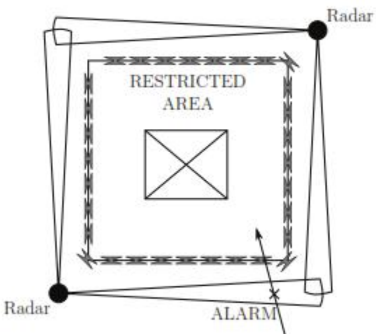

Figure 8. Principle of barrier mode

In both cases the UAVs were detected.

Apart from radar based techniques, there are other approaches for detecting/tracking UAVs: utilization of Radio Frequency (RF) signals radiating from UASs, acoustic sensors, computer vision, and sensor fusion. [12]

One possible approach to detect/track UASs is to use signals that are broadcasted from the UASs. Such signals can be control signals between the UAS and the remote operator (typically at 2.4 GHz). In [13], three possible approaches are considered for drone detection: analysis of the reflected signal from the propellers, sniffing the communication between the drone and its controller, and analysis of the reflection patterns from vibration of the drone's body. In [14], frequency hopping spread spectrum signals from a UAS are extracted using SDRs to detect (and jam/spoof) the UAS. This approach can be generalized to train a classifier (neural network) for identifying unique RF transmission patterns from popular commercially available UASs.

Yet another approach for detecting/classifying UASs is through the use of acoustic sensors [15]–[19], which can detect UASs at distances ranging from 20 m [15], [19] up to 600 m [16]. For example, in [15]–[17] microphone arrays have been used which can (through beam forming) find the direction of the drone in 3D. Hence, using more than one microphone arrays, location of the drone can be identified. In all these three works, a known signature of the drone (which should be captured a-priori) is searched within the real-time spectrogram of the captured acoustic signals. Acoustic detection of a drone can be completely passive and relatively inexpensive; however, they get impacted from factors such as wind and other background noise.

Finally, detecting/tracking of unauthorized drones can be achieved using computer vision techniques, which enjoyed extensive advances within the past years [20]. For example, in the ImageNet Large Scale Visual Recognition Competition (ILSVRC), the average detection precision has reached 0.80 in 2016 from 0.22 in 2013. While they suffer from line of sight limitation (due to cloud, fog, dust), merits of computer vision techniques for drone detection include: detecting drones that do not have RF transmission; passive and cheap optical sensors; and inherent directional accuracy. An approach such as in [21] can be used to track a moving and rotating UAS in a complex and dynamic background. Visual/thermal cameras with different fields of views (FOVs) can be used simultaneously for faster and more accurate detection. In [22] a collaborative smart phone sensing based drone detection is studied which can detect shape, color, orientation of the drones.

For accurate and quick detection/tracking of UASs, data fusion techniques that may simultaneously use information from multiple different types of sensors can be used: in [23] joint use of a 94 GHz mmWave radar and a high resolution optical camera is considered [12]

V. CONCLUSIONS

W band radars cam make substantial contributions to avoid the growing threats from the UAVs, however further improvements are needed for an operational UAS-detection radar system in the W band. [10]

This article summarizes a study regarding the detection of UAVs using different radars with different frequency bands and different UAV detection methods. The work presented in this paper can definitely help future researchers have an overview in this study.

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